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CONTINUATION OF HIGH ALTITUDE CLEAR AIR TURBULENCE STUDIES

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CONTINUATION OF HIGH ALTITUDE CLEAR AIR TURBULENCE STUDIES

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ABSTRACT

Data obtained from U-2 HICAT flights were used to relate the magnitude of horizontal temperature changes to flight conditions. The findings can be used in evaluating the effectiveness of aircraft-borne sensors that rely on temperature measurements for the remote detection of clear air turbulence.

Gust velocity changes of at least 20 fps occurred in all but one of 68 turbulence encounters in which temperature changes were 3C or higher, and in only 13 of 97 cases with changes of less than 1C. Although short period temperature variations were generally small during smooth flight and increased in magnitude during rougher flight, exceptions were noted. Large horizontal temperature changes were observed during smooth flight in the vicinity of severe turbulence and on occasional flights where the temperature changed appreciably over shallow vertical layers. Small changes were sometimes noted during moderate turbulence when the vertical temperature structure was nearly isothermal.

Frequencies of true gust velocity changes were calculated for flights over varying terrain. The average number of vertical gust changes per 1000 flight miles increased substantially for flights over high mountains, the difference in terrain affects being most notable for large gusts. Turbulence decreased with altitude above 45,000 ft, as expected. However, the decrease was much less over mountains, especially for moderate to greater turbulence. The ratio of turbulent to total flight miles was only 70 percent of the value previously arrived at in the HICAT program (33 percent for turbulence $\geq$ moderate). when "smooth" and low intensity portions of the turbulent encounters were properly identified.

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PART I

TEMPERATURE GRADIENTS IN STRATOSPHERIC TURBULENCE

SECTION I

INTRODUCTION

Vertical motions accompanying stable lapse conditions should produce temperature oscillations at least at the onset of turbulence (Atlas, 1969). These oscillations are normally of smaller magnitudes than are observable at the limiting resolution of upper air temperature devices commonly employed in radiosondes. To detect detailed temperature changes associated with turbulence, more sensitive devices with shorter response times are necessary. Suitable devices can be aircraft-mounted and be capable of measuring scales on the order of those present in the turbulence motions.

Recently increased attention has been directed toward the possibility of detecting clear air turbulence in flight using remote sensing instruments which sense temperature oscillations by infrared techniques. The principle behind this method has been discussed by Weiss (1969). A spectral radiometer measures infrared radiation emitted by CO_2 in a column of air at a particular wavelength band. The variation of the infrared radiation in the CO_2 band is strongly dependent on the temperature variation. The instrument's effectiveness in sensing turbulence depends largely upon whether the turbulence occurs in proximity to significant temperature variations. Others who have described the infrared method of detecting turbulence, include Jiminez (1969), Astheimer (1970), and Broussaud, et al (1970).

In this report it is inferred that variations in stratospheric turbulent gusts tend to occur on the same length scale as the wavelength of horizontal temperature oscillations. Time histories of records from entire flights and from portions of flights in and around turbulence serve to compare and classify temperature environments typical of flight conditions ranging from smooth to severely turbulent. The High Altitude Clear Air Turbulence (HICAT)

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program provided the data source. Simultaneous measurements of temperature and gust velocities from this program represent the best available information for evaluating temperature and gust correlation procedures for aircraft operations at altitudes greater than 45,000 feet.

SECTION II

PREVIOUS STUDIES

Pioneer investigations of in-flight measured temperature gradients in turbulent regions have been undertaken by Kadlec (1963, 1964, 1965). Much of Kadlec's data were from commercial jetliner flights. In a recent study of jetliner turbulence encounters Kadlec (1968) found that the average total temperature change in moderate turbulence was 5C, and only 3C in smooth or very light chop conditions. McLean (1965) found poor correlation between horizontal temperature gradients measured on the same scale as Kadlec's and moderate or greater turbulance for B-47 flights at jet stream levels. The B-47 flights near known mountain waves and above convective activity were excluded from McLean's study. In general, Kadlec's, McLean's and other studies have indicated that the magnitude of short period horizontal temperature changes appears to be much less below the tropopause than in the stratosphere.

Results summarizing various investigations of in-flight measured temperature changes and stratospheric turbulence are presented in Table I. Two cases from flights in the troposphere are also shown.

TABLE I

CHANGES IN AMBIENT TEMPERATURE IN THE STRATOSPHERE AND TROPOSPHERE AS MEASURED BY AIRCRAFT

Author	Location	Aircraft	Altitude (ft)	Turbulence	ΔT (mi)
Helvey (1967)	Bishop, Cal.	U-2	60,000	mod-sev	16C in 3
Ehernberger (1968)	Western U.S.	XB-70	63,500	very light	11C in 6
MacPherson & Morrissey (1969)	Albuquerque, N.M.	RB-57F	55,000	light-mod	21C in 6
Burnham (1970)	Unknown	Canberra	46,000	severe	28C in 5
Crooks et al (1968)	Denver, Col.	U-2	55,500	mod-sev	19C in 18
Waco (1970)	Albuquerque, N.M.	U-2	53,800	severe	12C in 4
Mather (1967)	Edmonton, Canada	T-33	15,000	unknown	11C in 6
Weiss (1969)	New York, N.Y.	T-33	35,000	mod-sev	5C in 2

SECTION III

HICAT PROGRAM

Initial flights of the HICAT program were conducted in 1964 using an instrumented U-2 equipped with a digital pulse code modulation system to record measurements of three components of the gust velocity and a Rosemont Model 102E2AL temperature sensor. Sampling rate was 25 sec^{-1} corresponding to a nyquist frequency of 12.5 cps in the time hisotries and power spectra.

In March 1968, the program was completed following 285 flights which covered over 500,000 miles between the altitudes 45,000 and 70,000 feet. Geographic areas scanned for turbulence included the continental United States, Alaska, Hawaii, Australia, New Zealand, the Carribean and Panama, eastern Canada, England and France. A comprehensive description of the program, including instrumentation, may be found in Crooks, et al (1967, 1968) and Ashburn, et al (1968, 1969, 1970).

Analysis of the HICAT records produced the following interpretations. Terrain effects had dominant influence on turbulence distribution. The portions of flight mission tracks over which turbulence was encountered (expressed as the ratio of turbulence encounter distance to total flight distance in percent) increased from 2.7 percent for flights over water and flatland to 4.9 percent for those over high mountains (local relief differences greater than 7000 feet). Moderate and severe turbulence was 3-1/2 times more frequent over high mountains. All but three of the 31 encounters with turbulence greater than moderate occurred over high mountains (relief > 7000 feet).

Seasonal and altitude trends in the distribution of turbulence were also evident. Moderate or greater turbulence occurred four times more often in

winter and spring than in summer and fall. Turbulence decreased rather sharply with altitude over flat terrain (very few encounters above 60,000 feet) while the dropoff was minimal up to 65,000 feet over mountains (Waco and Ortasse, 1969).

The empirical relationship between temperature changes and true gust velocity magnitudes is discussed in the following section.

SECTION IV

HICAT GUST VELOCITY AND TEMPERATURE CORRELATIONS

The maximum change during a 20 second (approximately 2-1/2 statute mile or 4 km) period of temperature and gust velocity for 272 HICAT turbulence runs has been plotted in Figure 1. The temperature changes were computed for horizontal flight only (altitude change less than 100 feet). The gust component, usually lateral or longitudinal, with the largest maximum change was used. The interval 2-1/2 miles is approximately half the distance of the longest wavelengths observed in most HICAT gust records and was selected as a convenient reference interval. In atmospheric processes, large scale random motions (wavelengths on the order of five miles) tend to be associated with large horizontal temperature gradients since the motions involve appreciable vertical displacement of air.

There appears to be a large scatter in the data shown in Figure 1, especially for large temperature changes. However, the linear correlation coefficient ($r = 0.74$) is significant. This is more readily observed in Table II where temperature and gust velocity are grouped in three classes. Only 13 percent of the turbulent runs had gust velocity changes of 20 fps or greater when the maximum temperature change in a 20 second period was less than 1C. Conversely, all but one of the 68 runs with temperature changes of 3C or greater had gusts approaching moderate or severe intensity ($\geq$ 20 fps).

As shown in Figure 2, the logarithm of maximum gusts appears to follow a normal distribution, even when separate terrain categories are considered. Turbulence encounters over mountains (local relief differences > 3000 feet) had consistently higher frequencies of maximum gusts with given magnitude than low relief cases. Actually, 50 percent of runs over high mountains had

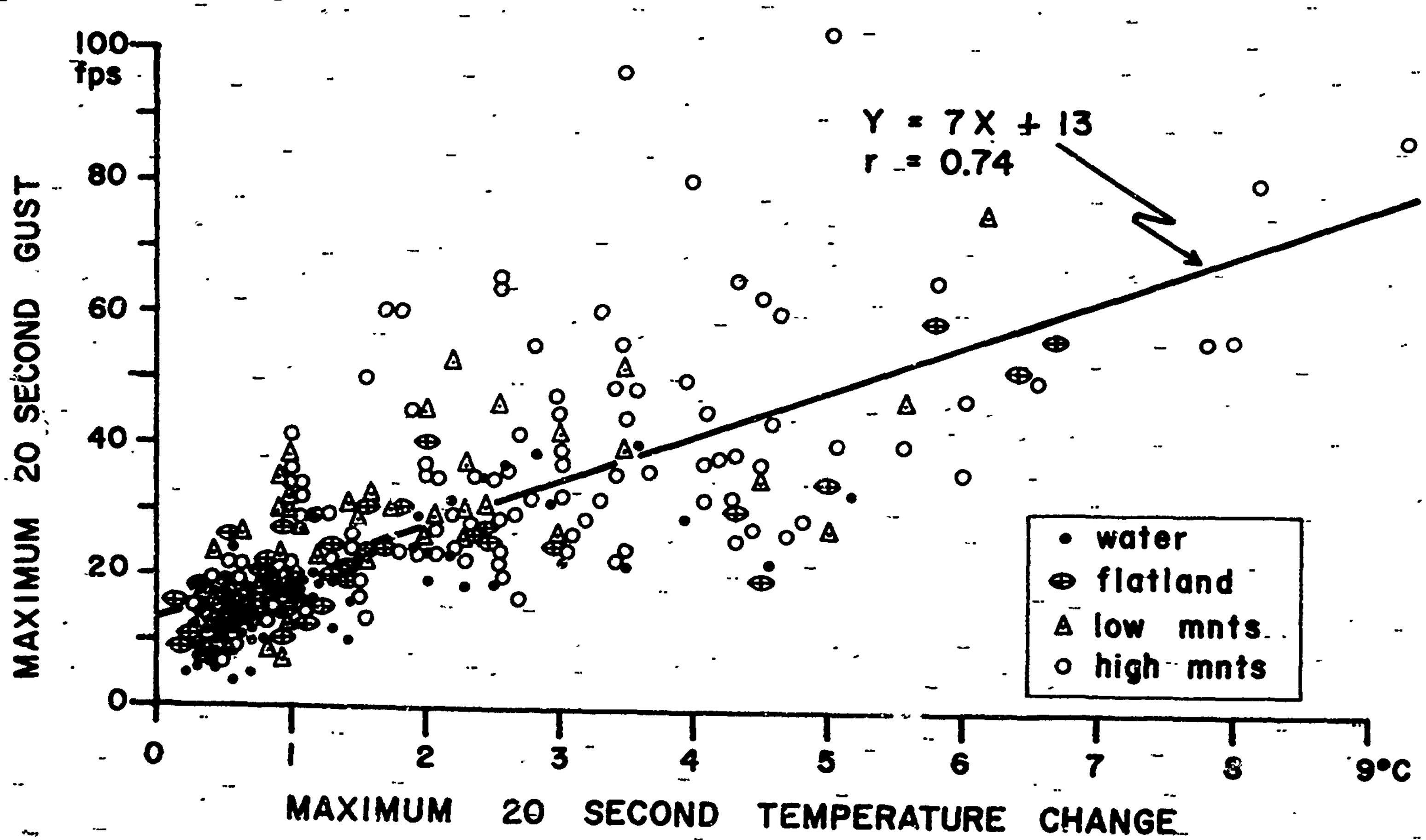

Figure 1. Maximum change in gust velocity as a function of maximum temperature change during 20 second (2-1/2 mile) periods for 272 HICAT turbulence encounters (runs).

TABLE II

NUMBER OF TURBULENT RUNS IN EACH CLASS OF
MAXIMUM TEMPERATURE AND GUST VELOCITY CHANGES DURING 20 SECOND PERIOD

		Maximum Gust Change		
		0 - 19	20 - 39	≥ 40 fps
Maximum	< 1C	84	13	0
Temperature	≥ 1C, < 3C	22	71	14
Change	≥ 3C	1	34	33

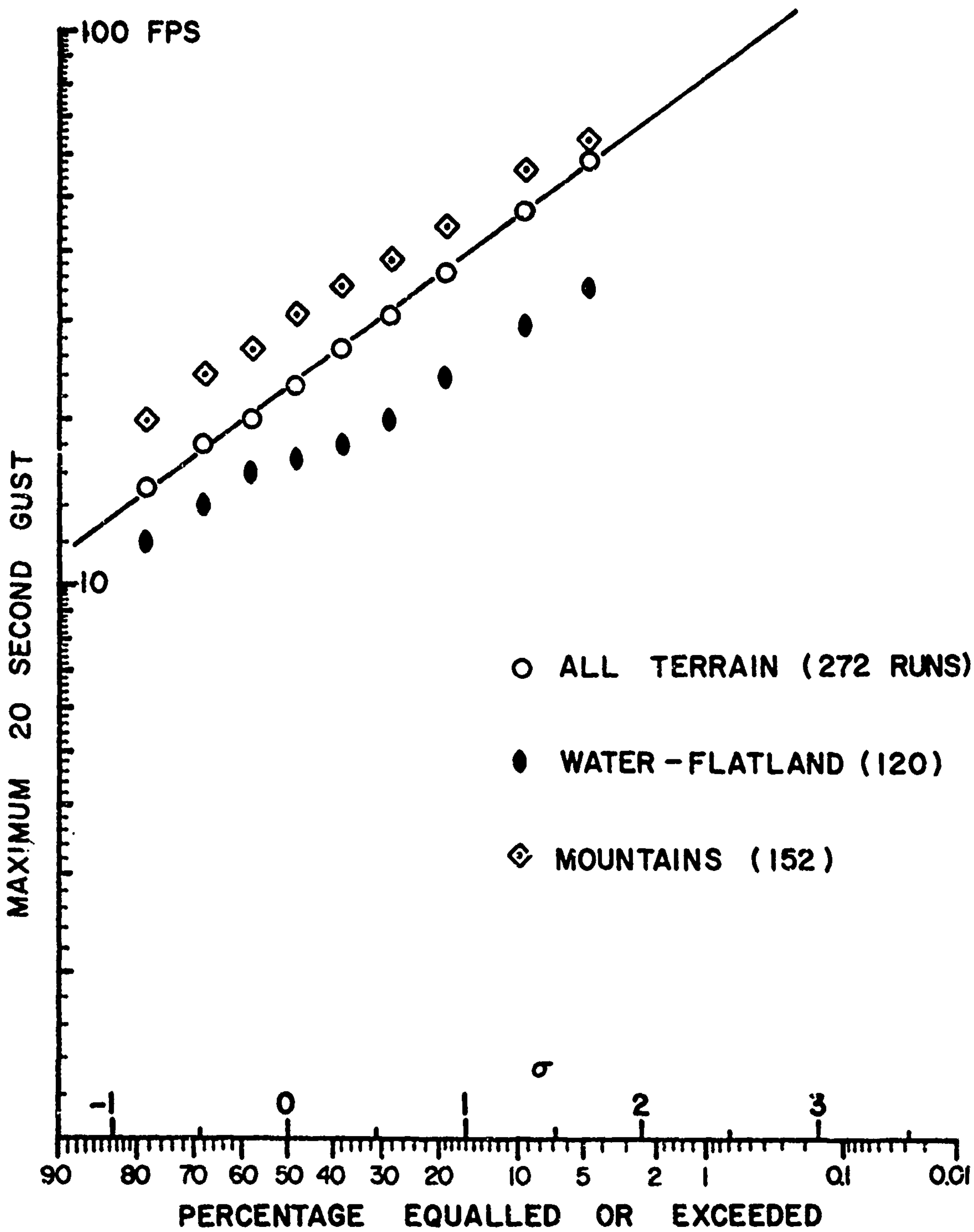

Figure 2. Percentage of runs with maximum gust velocity change during 20 second periods equalled or exceeded as a function of terrain. Ordinate is logarithmic, abcissa is normal.

gust velocity changes in excess of 30 fps (10 percent in excess of 55 fps), whereas Figure 2 shows that only 10 percent of the runs over low relief terrain had gusts > 30 fps.

The distribution of maximum temperature changes (Figure 3), like that of the maximum gusts, is characterized by higher values associated with rough terrain. However, the extreme changes are not appreciably larger for mountain-related turbulence. This is evidenced in Figure 3 by the deviation from log normal of both mountain and all terrain distributions. For given frequencies the magnitude of maximum gusts consistently increases with an increase in maximum temperature change classes (Figure 4).

Figure 5 shows the distribution of the elapsed time between the initial encounter with turbulence and the beginning of the maximum gust for 104 runs over high mountains. The distribution is log normal with 50 percent of the cases having a time difference of about 55 second (seven miles). It may be observed that the time of occurrence of the maximum gust in relation to the turbulence start time is independent of turbulence severity. In many individual cases, however, gusts of appreciable magnitude were encountered prior to the most severe gust; these being generally associated with fairly large temperature changes. Consequently, the time distribution between the onset of turbulence and the encountering of, for example, the 90 percent gust would show a tendency towards shorter time periods than are found in Figure 5. The time difference between the beginning of the period with the maximum temperature change and onset of the maximum gust was investigated for turbulence encounters over high mountains. Here it was found that the largest temperature changes were usually experienced in close proximity to the largest gusts, with a slight tendency for the maximum temperature change to precede the maximum gust. However, maximum temperature changes occurring 20 seconds or more preceding or following maximum gusts were generally accompanied by appreciable gusts.

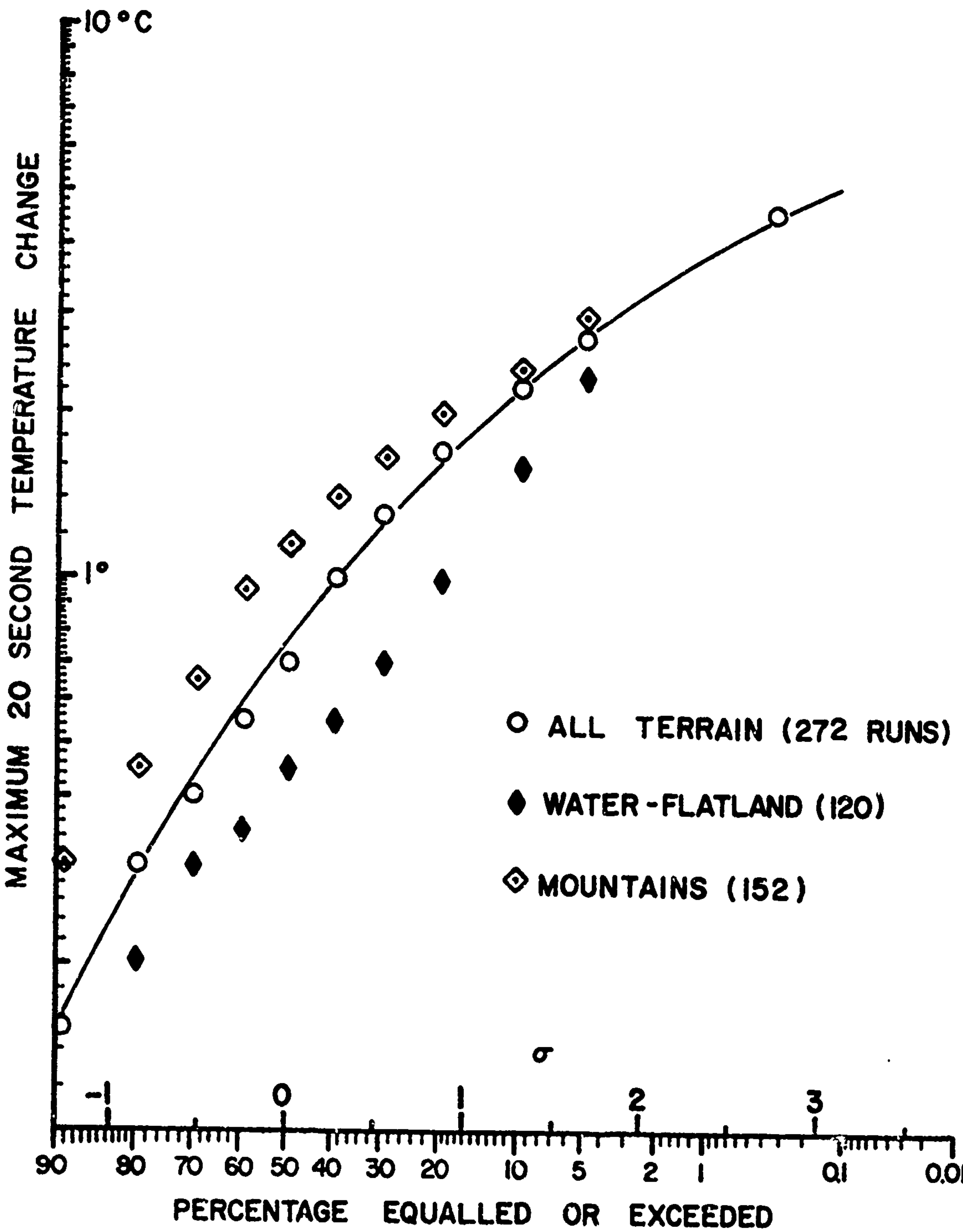

Figure 3. Percentage of runs with maximum temperature change during 20 second periods equalled or exceeded as a function of terrain.

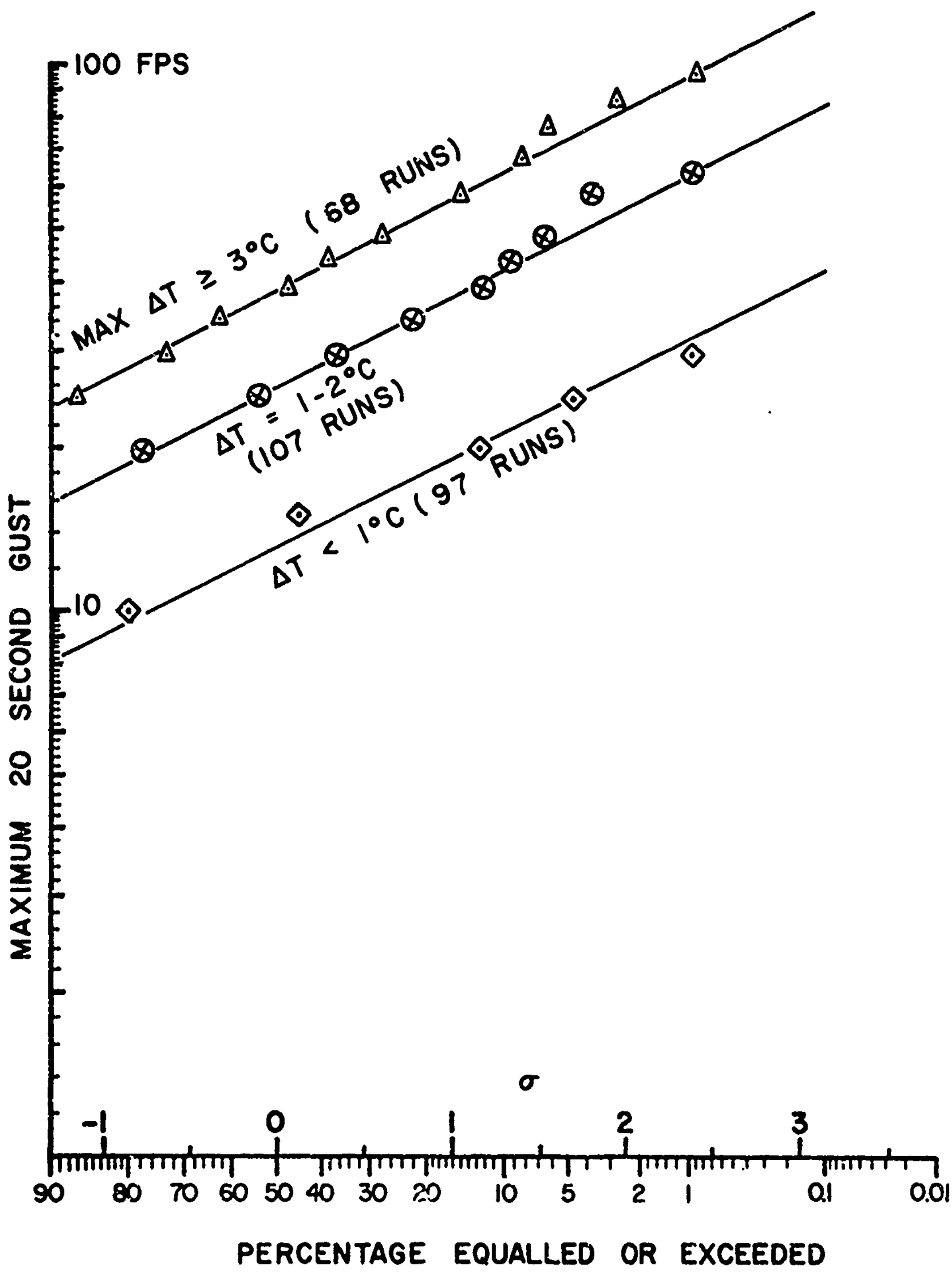

Figure 4. Percentage of runs with maximum gust velocity change equalled or exceeded as a function of maximum temperature change.

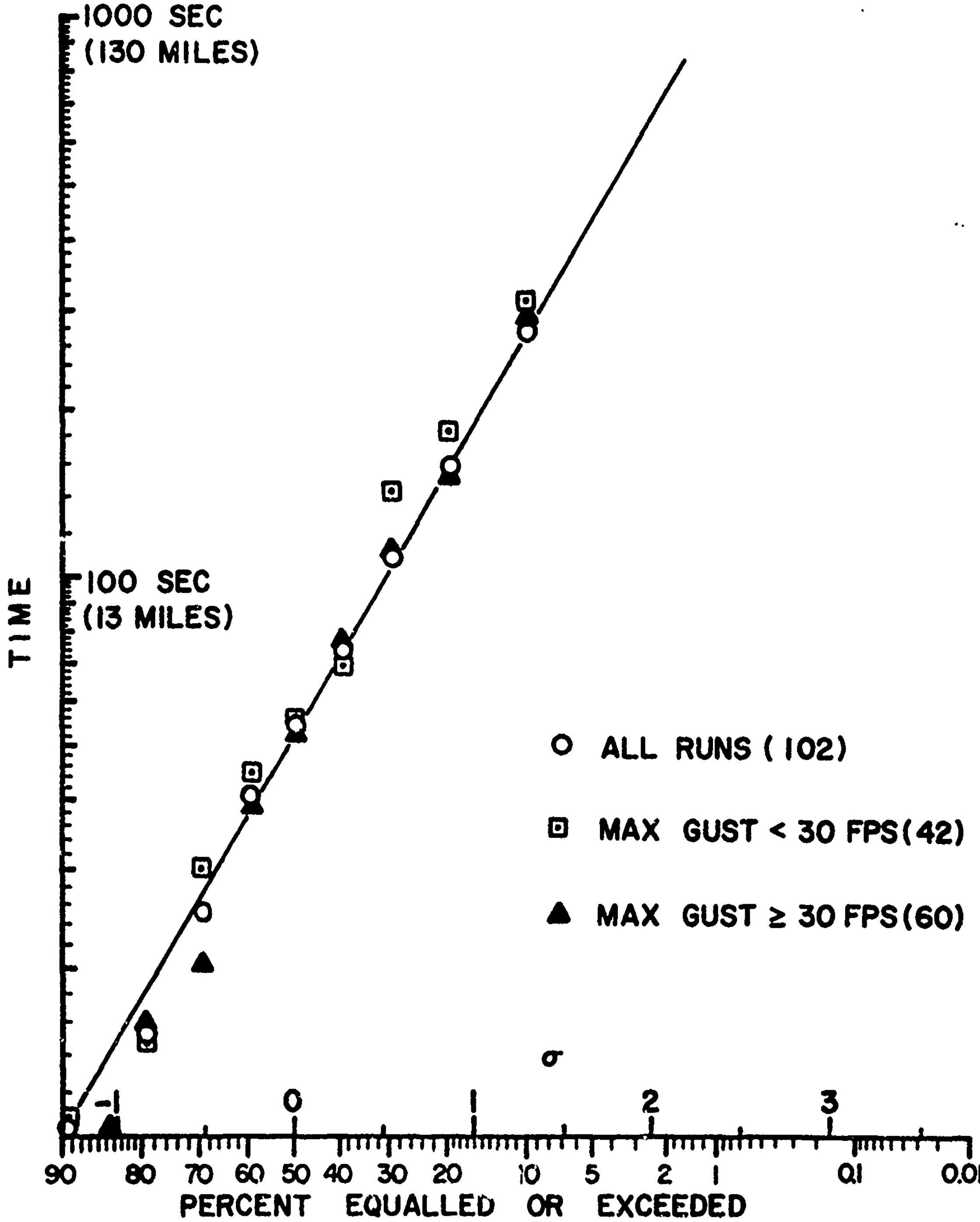

Figure 5. Cumulative distribution of elapsed time from initial encounter with turbulence to the maximum gust. Abcissa is percentage of high mountain runs with elapsed time equalled or exceeded. Two intensity classes of the maximum gust are shown.

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SECTION V

TIME HISTORIES

Several examples of gust velocity and temperature time histories from HICAT turbulence encounters are presented in Figures 6 - 12. These serve to illustrate the relationship between temperature and gust velocity variation, showing especially their unique correspondence when considering individual cases.

Temperature and pressure altitude records from HICAT flights 255 and 280 are shown in Figure 6. Flight 255 was in smooth air while severe turbulence was encountered during Flight 280. The time histories were compiled from 10 seconds (250 point) averages sampled each minute.

Flight 255 was a ferry flight from Florida to California. The latter half of the flight was extensively over mountains. Turbulent portions of Flight 280 were above the Rocky Mountains, west of Denver, Colorado. Although possessing similar terrain features, these flights exhibited contrasting patterns in temperature variation, depending primarily on whether the flight conditions were smooth or turbulent. Note, however, that during Flight 280 the temperature changes significantly in smooth portions between turbulence encounters. This characteristic was typical for flights with turbulence of moderate or greater intensity (Waco, 1970 b). In 63 flights, selected on the basis of adequate records, the average change in temperature between readings sampled every minute for 10 minute flight segments varied as follows:

	Avg ΔT/Min
Smooth flight (no turbulence within 200 mi).	0.26 C
Smooth flight (turbulence > light within 200 mi) . .	0.80 C
Rough flight (turbulence > light).	1.24 C

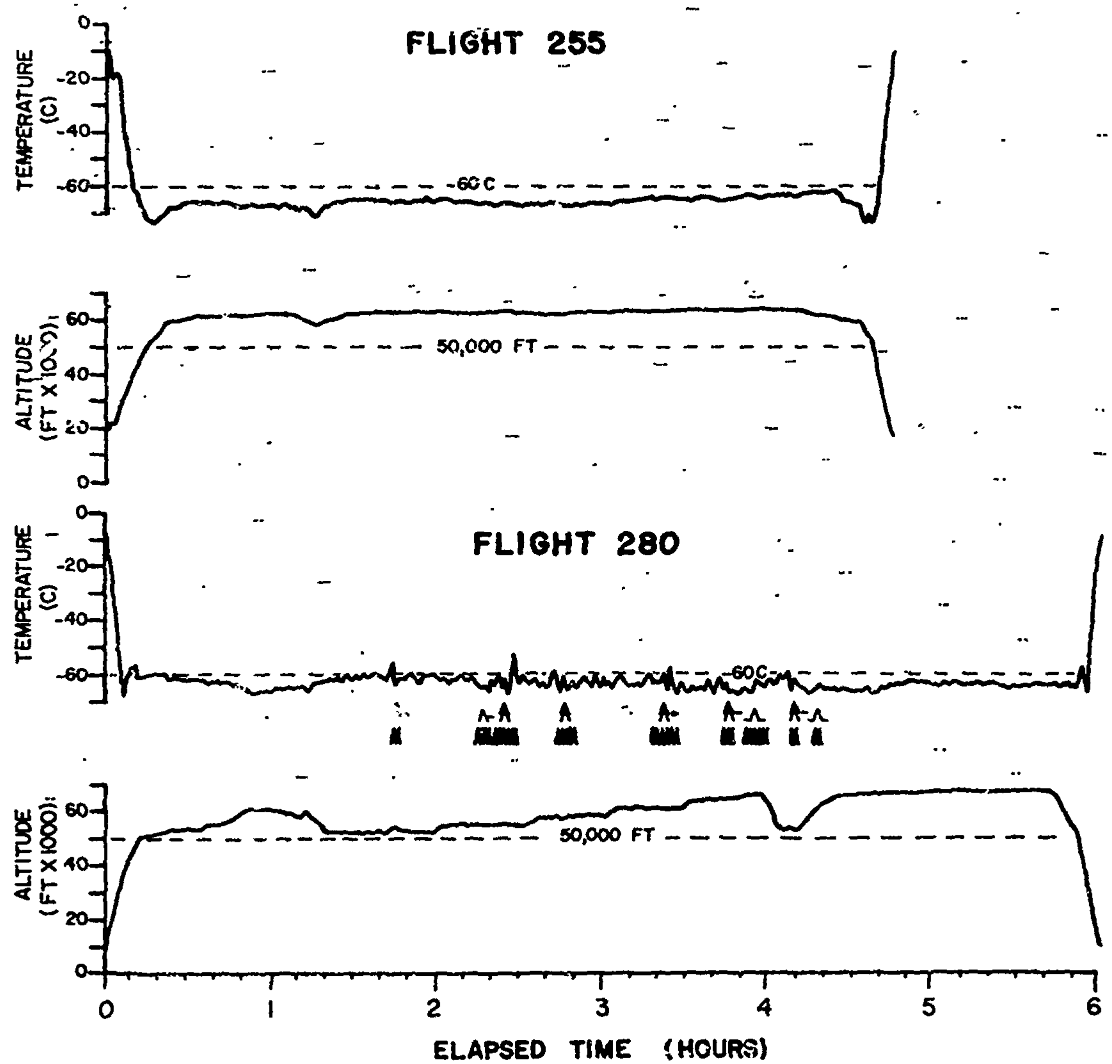

Figure 6. Time histories of temperature and pressure-altitude for flight 255 (smooth) and Flight 280 (turbulent). Turbulence symbols: ⋀ light; ⋀ moderate; ⋀ severe. Dash lines are for lesser intensity

Two flight segments (Figure 7) illustrate the nearly isothermal pattern along horizontal flight common with most of the HICAT temperature records taken during smooth flights. Time history data has been sampled at 25 sec^{-1} pps. Flight 100, Run 8, flown over flat terrain in southeast Australia, had no turbulence. Very light turbulence occurred during Run 7 of Flight 258, above mountains southwest of Bakersfield, California.

In Figure 8 are presented the temperature, pressure altitude, and gust velocity of four turbulence encounters, one for each terrain, containing the largest gust velocity changes observed during the HICAT program. In all cases the gust velocity changed over 50 fps in 20 seconds and in the high mountain case it exceeded 100 fps. Large temperature changes, clearly evident for each terrain-associated turbulence encounter, did not always occur throughout the entire turbulent period as is evidenced by Run 5 of Flight 102. This flight over low mountains had largest changes concentrated in the area containing the largest gust.

The locations of the turbulence encounters shown in Figure 8 varied as follows: The water case (Flight 182) was between Scotland and Denmark at 48,000 ft altitude. A high level jet with 73 kt winds at 150 mb was reported 200 miles to the west. Flight 198, flown at 51,000 feet over a line of thunderstorms near Oklahoma City, had winds at flight level approaching 100 kt. The low mountain run (Flight 102) was at 61,000 feet near the Great Diving Range in southeast Australia. Nearby radiosonde stations reported winds greater than 100 kt at 50,000 feet and 90 kt at 55,000 feet. Flight 280 took place at 58,000 feet over the mountains west of Denver; although winds were rather light near flight altitude and only moderately strong above 200 mb, below 200 mb significant winds prevailed, with mountain wave conditions present.

Figure 9, which shows the temperature, pressure altitude, and three components of the gust velocity for Flight 280, Run 6, illustrates the largest temperature change (19 C) during the entire HICAT program. This change accompanied severe turbulence at 56,000 feet in the same location and 23 minutes preceding

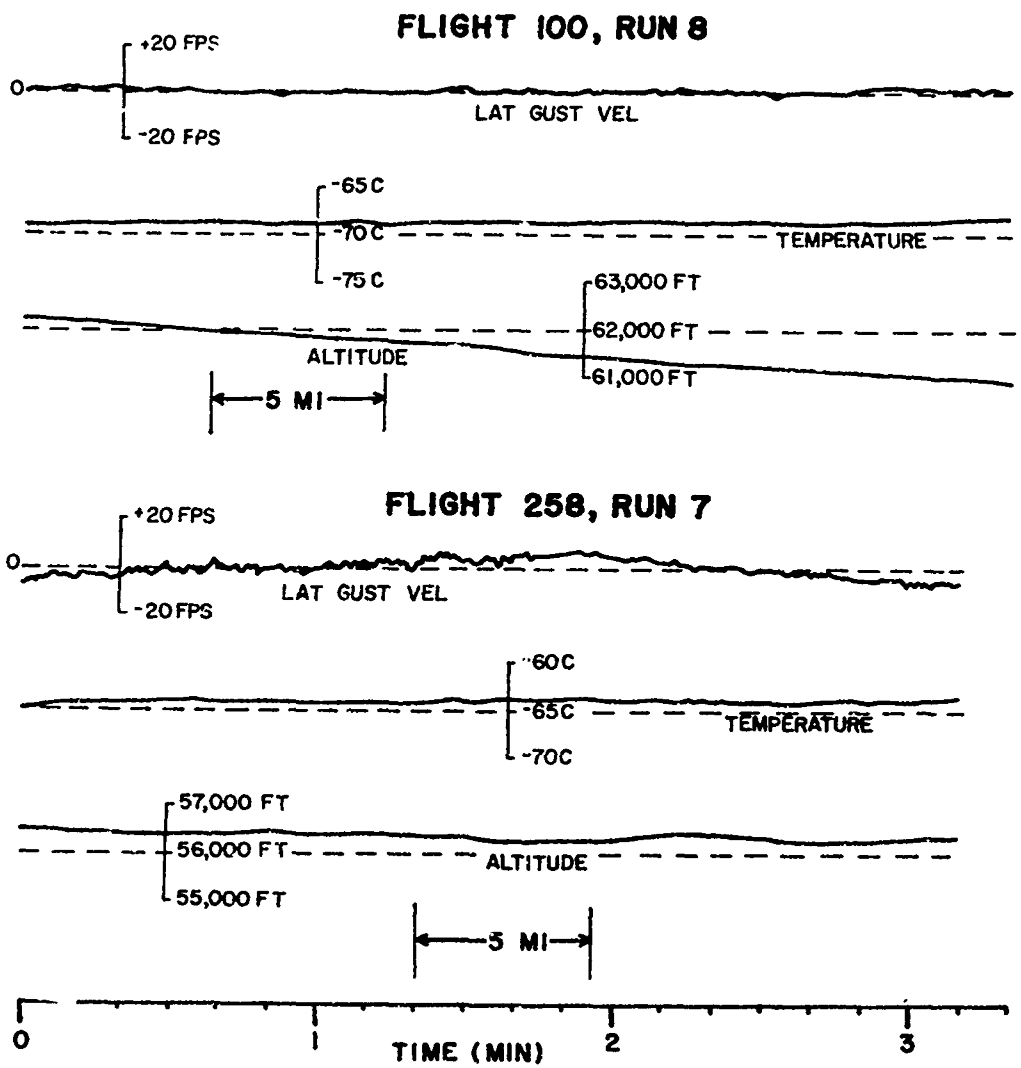

Figure 7. Time histories of the lateral gust velocity, temperature, and pressure-altitude for flight 100, run 8 (smooth), and flight 258, run 7 (very light turbulence).

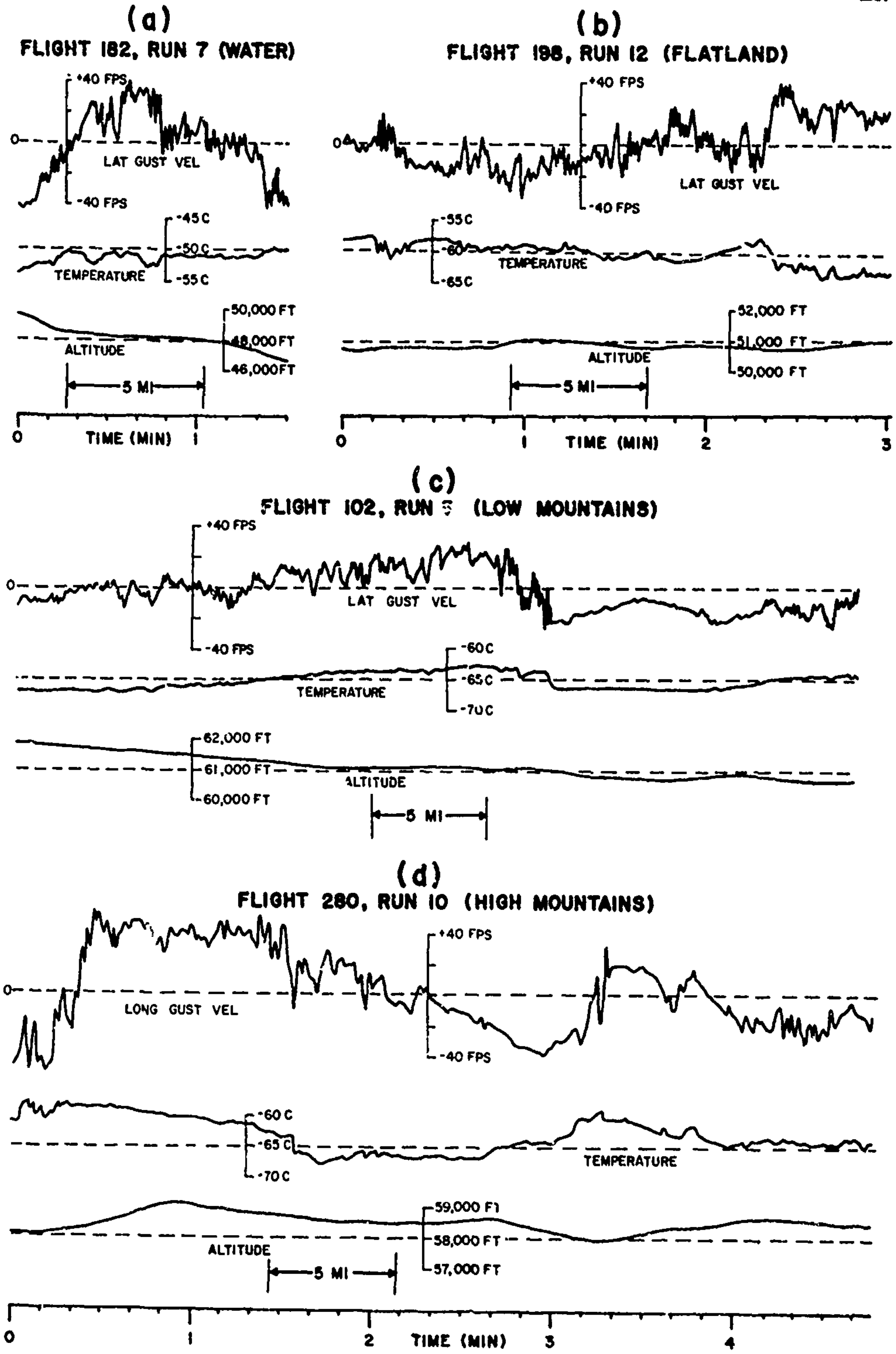

Figure 8. Time histories of the gust velocity component with the maximum change in 20 seconds, temperature, and pressure-altitude for (a) flight 182, run 7 (water), (b) flight 198, run 12 (flatland), (c) flight 102, run 5 (low mountains), and (d) flight 280, run 10 (high mountains).

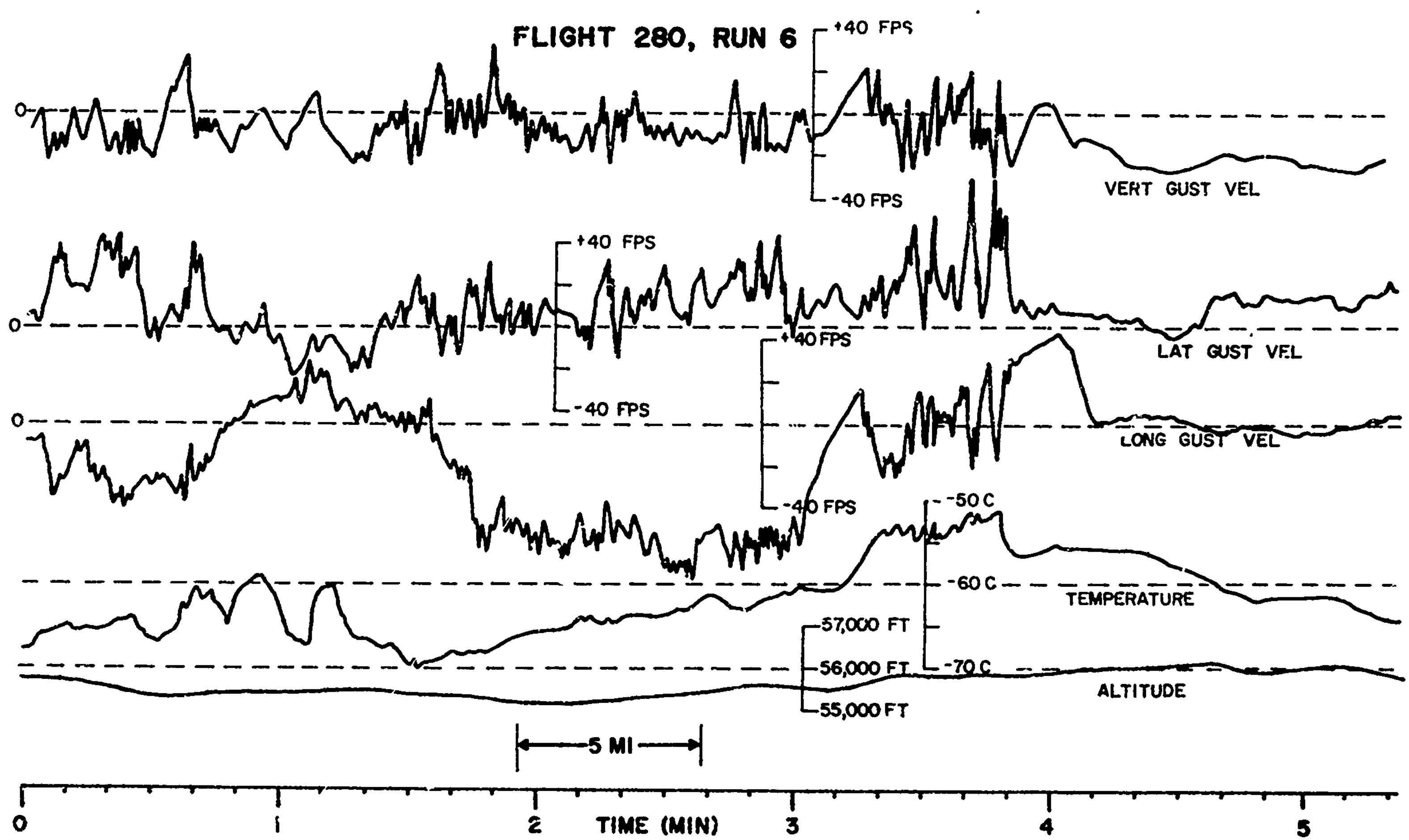

Figure 9. Time histories of the components of gust velocity, temperature, and pressure-altitude for flight 280, run 6.

the high mountain case in Figure 8 (Flight 280, Run 10). Run 6 was flown towards the mountains (into the wind) and Run 10 (Figure 8) away from the mountains. In both Runs 6 and 10 of Flight 280, the most severe gusts were found near the warmest zone or the trough portion of the mountain wave (characterized by descending air upwind). This relation was also noted (Helvey, 1967) in analysis of U-2 flights above the Sierra Nevada Mountains near Bishop, California; these flights were not associated with the HICAT program.

Although HICAT records yield strong evidence that in flight measured horizontal temperature changes are well correlated with turbulence, exceptions to this relationship cannot be ignored. Clear air turbulence may occur near neutral temperature stratification where vertical motions possibly will not produce significant temperature changes (Atlas, 1969). In addition, only small vertical motions may produce large horizontal temperature perturbations if the vertical temperature profile shows significantly large changes over thin layers (Waco, 1970 c). Figures 10 - 12 present examples of these two situations.

Figure 10 shows time histories of temperature and pressure altitude for two flights, one (Flight 251) with large temperature changes and insignificant turbulence and the other (Flight 107) with relatively minor temperature perturbations in areas of extensive turbulence. Individual runs have been selected from these two flights (Figure 11) to illustrate finer details of the concurrent turbulence and temperature variations.

During Flight 251 (Figure 10) the aircraft generally flew near 58,000 feet. Records from radiosonde stations along the route revealed an unusually high tropopause with sharp warming in the layer between 55,000 and 60,000 feet. Either minor changes in altitude or relatively small vertical motions could conceivabley have produced large temperature oscillations along a horizontal flight path. In Figure 11, the run selected from Flight 251 shows horizontal temperature changes of 5 C along with very light turbulent conditions.

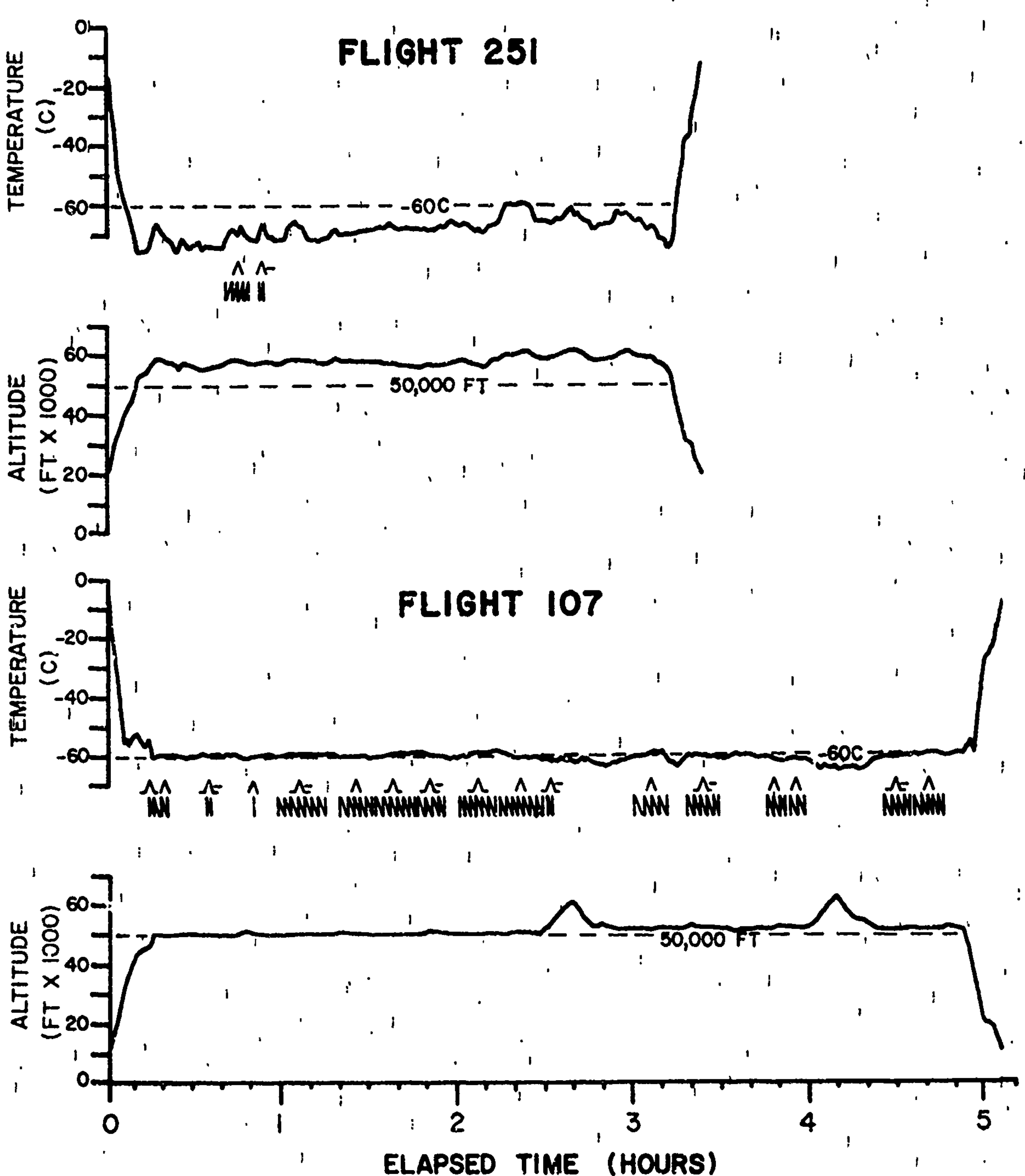

Figure 10. Time histories of temperature and pressure-altitude for flight 251 (smooth, large temperature changes) and flight 107 (turbulent, small temperature changes).

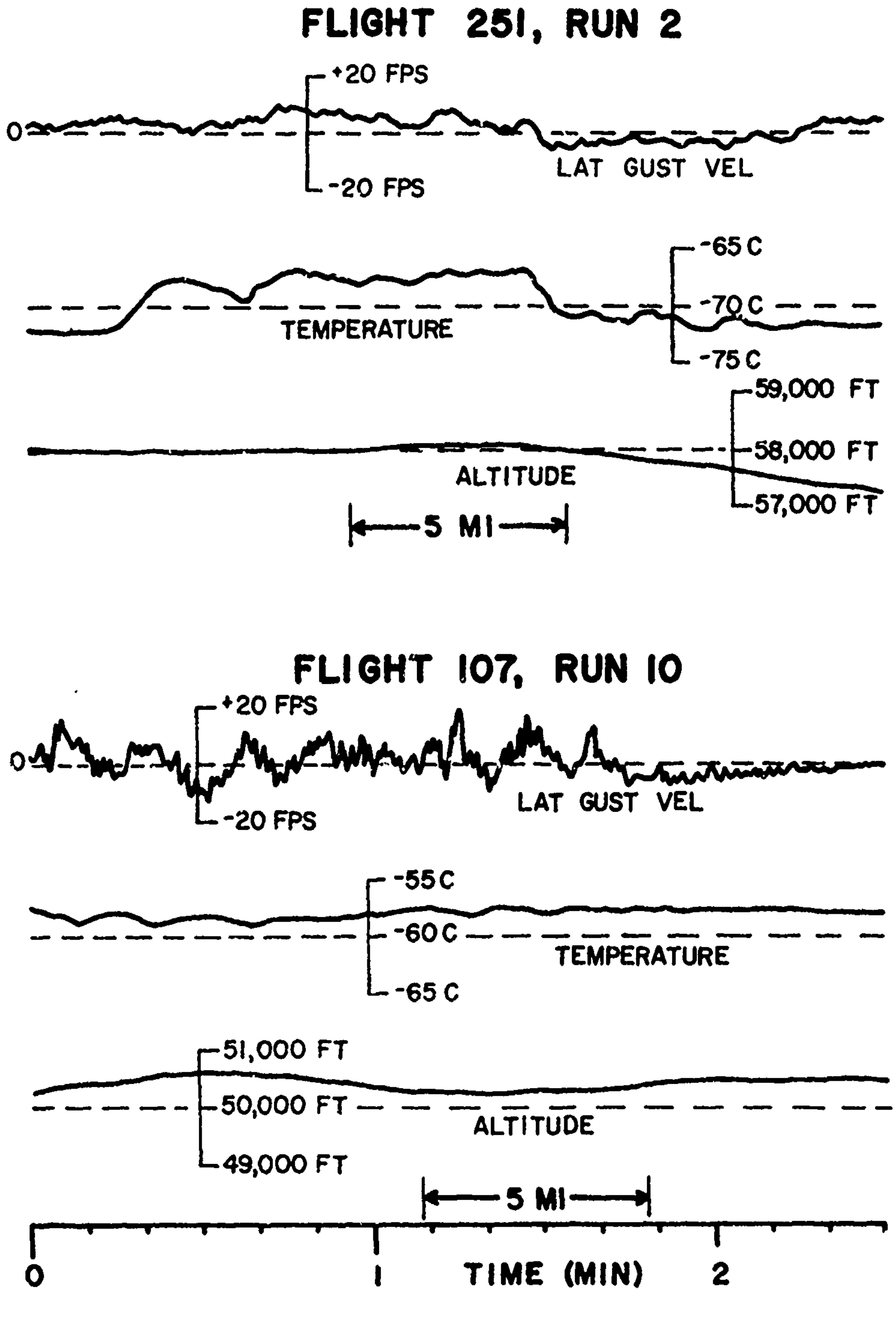

Figure 11. Time histories of the lateral gust vwlocity, temperature, and pressure-altitude for flight 251, run 2 (very light turbulence, large temperature changes) and flight 107, run 10 (moderate turbulence, small temperature changes).

During portions of Flight 107 (Figure 10) the aircraft changed altitude by several thousand feet but no appreciable temperature changes were noted. Radiosonde data verify the existence of a nearly isothermal lapse rate in the layer 50,000 to 60,000 feet and, in addition, rather weak horizontal temperature gradients between stations. In these homogeneous conditions small scale oscillations (turbulence scale) in air motions would not likely produce significant temperature variations. This is illustrated in Figure 11.

The final example (Figure 12) presents time histories of temperature, pressure altitude, and the longitudinal component of the gust velocity for two runs over and near the eye of Hurricane Beulah (1965). Run 1 was located directly over the eye, just above cloud tops at 54,500 feet. The vertical temperature profile, as measured by the aircraft and by nearby radiosonde stations, displayed a rather sharp increase in temperature (9 to 11 C) in the initial few hundred feet above the clouds. Because of the non-uniformity in the height of the cloud tops, and also in the height of the top of the tropopause (which is dependent on the height of the cloud tops) temperature oscillations were experienced as the plane flew in a relatively horizontal path near the tropopause. Temperatures were sampled from the bottom to the top of the sharp inversion layer above the tropopause. The highly stable inversion layer was also associated with fairly smooth flight conditions, presumably because of the absence of strong horizontal and vertical motions above the hurricane.

When the U-2 descended to cloud top level just north of the eye, light to moderate turbulence was encountered (Figure 12). The temperature varied only slightly which is not surprising in view of the nearly isothermal structure in the vertical at and below cloud top level.

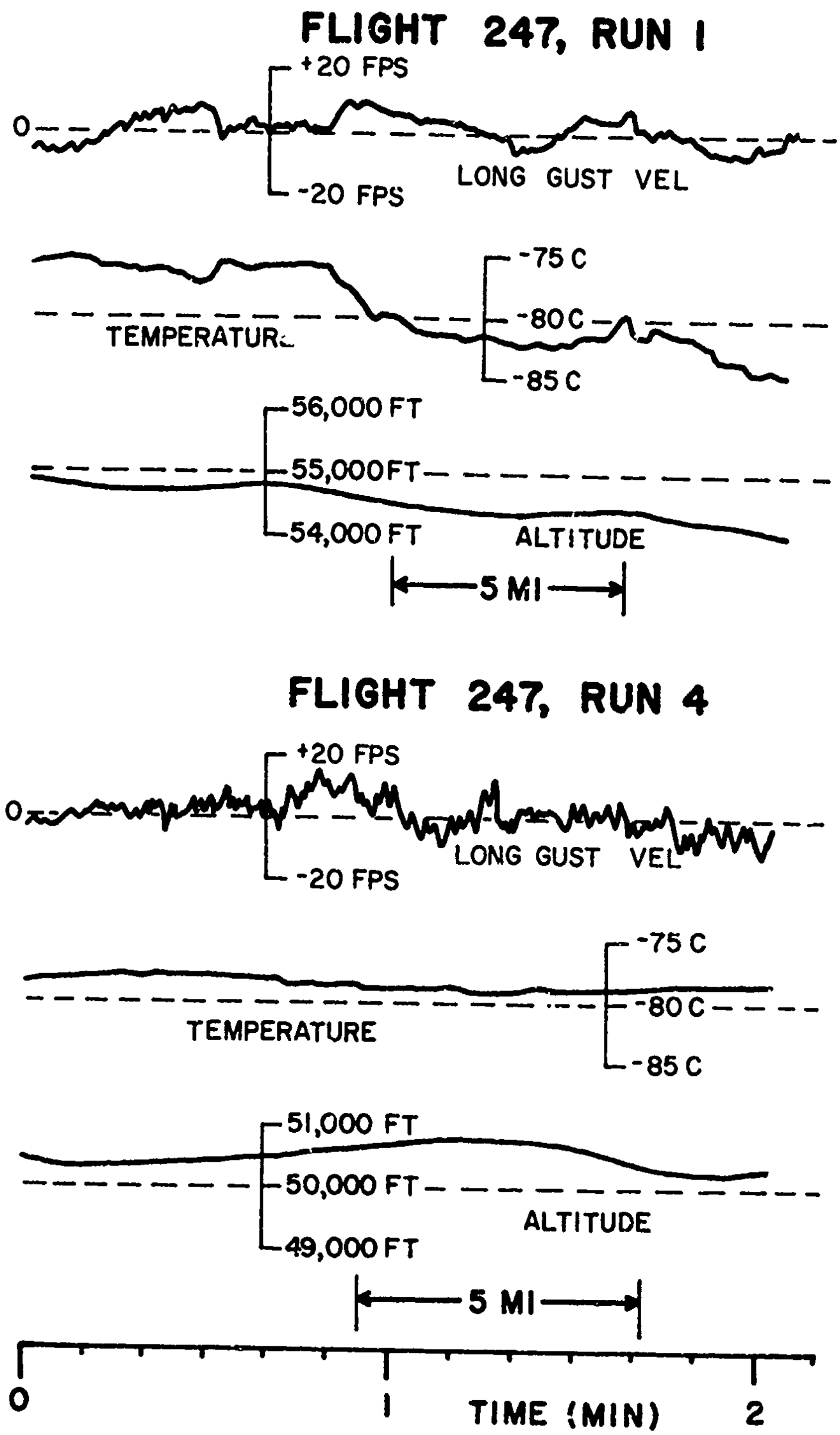

Figure 12. Time histories of the longitudinal gust velocity, temperature, and pressure-altitude for flight 247, run 1 (very light turbulence, large temperature changes) and run 4 (light-moderate turbulence, small temperature changes).

SECTION VI

SUMMARY AND CONCLUSIONS

Horizontal temperature changes are sufficiently correlated with turbulence in the stratosphere to warrant the use of temperature information in warning pilots of approaching hazardous conditions. Temperature changes would have to be detected ahead of the aircraft since they tend to occur nearly simultaneously with the more severe gusts. For example, if the aircraft were flying at speeds in the range of 1500 to 2000 mph, a 15 second warning would require detection six to eight miles in advance of the aircraft.

Evaluation of HICAT data has shown that temperature changes of appreciable magnitude can occur up to several miles away from moderate or severe turbulence. In these situations temperature changes could be used as advance warnings of impending turbulence if the aircraft's heading were in the direction of the turbulence. On the other hand, a false alarm could occur if the temperature changes were experienced by an aircraft flying along the periphery of a turbulent area. Also, it would be hard to distinguish on a detection basis between situations where moderate temperature changes preceded severe turbulence or coincided with turbulence of lesser intensity.

The relation of U-2 measured horizontal temperature changes to high altitude turbulence may be summarized as follows:

1. Nearly all moderate or severe turbulence encounters were accompanied by short period temperature changes of appreciable magnitude and only rarely were large temperature changes found in the absence of intense turbulence.
2. Relatively large temperature changes appeared to be not uncommon in smooth regions near fairly intense turbulent areas.

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3. In certain situations consideration of the vertical temperature structure was crucial in understanding the reasons for variation in observed temperature changes in horizontal flight while the degree of turbulence may have been of secondary importance.

4. Large temperature changes were more common with turbulence over mountains, primarily because of the increase in turbulence severity.

Future work aimed at a better understanding of turbulence-temperature relations should include a more thorough investigation of temperature changes in smooth flight before statistical studies are attempted which relate the probability of encountering turbulence to the magnitude of in-flight measured temperature changes.

Acknowledgements

The author is grateful to Dr. Arnold Court, Geography Department Chairman and Climatology Instructor at San Fernando Valley State College, Mr. E. V. Ashburn, head of Lockheed's Atmospheric Physics section, and Dr. Glen Bowie of the Lockheed Acoustics section for their helpful comments in reviewing this paper.

PART II

HIGH ALTITUDE TURBULENCE MODELS DERIVED FROM U_{de} AND TRUE GUST VELOCITY MEASUREMENTS

SECTION I

INTRODUCTION

Turbulence exceedance models based on gust measurements are generally adopted from an evaluation of either derived equivalent (U_{de}) or true gust velocity data. In the present section, for the first time exceedance curves are developed from high altitude flight data consisting of both true and derived gust velocity measurements. Evidence from this study indicates that clear air turbulence severity varies with terrain more than was previously assumed (Ashburn et al, 1969).

In a subsection of this report true gust velocity time histories are used in demonstrating that considerably less time was involved in moderate or greater turbulence than had been presumed in Ashburn et al (1969), especially for flights above 60,000 ft over water.

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SECTION II

DERIVED GUST VELOCITY DATA

In the design of the HICAT program one of the purposes was to determine true gust velocity components along the aircraft flight path. The data would be used, among other things, as an aid in establishing probabilities of encountering gusts of given magnitudes. Several factors, including instrument failure, non-level flight, and high data noise levels, limited the number of runs suitable for deriving true gust velocity time histories to 27 percent of the total turbulence encounters (277 out of 987). Consequently, analyses which required records from a large percentage of the HICAT flights, such as the ratio of turbulent to total flight miles, usually included statistics on derived gusts (U_{de} data were available for 30 percent of the total turbulence encounters). The derived gust velocities were computed from cg normal accelerations of the U-2, the observations being based on several assumptions including a rigid aircraft, free of pitch, which entered the turbulence in level flight, plus other inferences about the shape of the gust profile (Crooks et al, 1967).

Flight miles with critical values of U_{de} rms equalled or exceeded have been determined for 199 flights totalling 313,700 miles. Table III summarizes the ratio of miles flown in U_{de} rms categories to total flight miles for four terrain classes. The data are plotted in Figure 13. Total miles flown over each terrain is represented by 100 percent on the ordinate scale. Classification by terrain is as follows: flatland: 0 to 3000 ft local relief; low mountains: 3000 to 7000 ft; high mountains: greater than 7000 ft. Turbulent and non-turbulent flight miles in regions of pattern maneuvers (i.e., repeated passes of the U-2 through the same general area) were adjusted downward so that sampling of turbulence in these areas would be representative of flight paths with no repetitious patterns. This adjustment

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TABLE III

RATIO (IN PERCENT) OF FLIGHT MILES IN U_{de} rms CATEGORIES TO TOTAL FLIGHT MILES BY TERRAIN

		U_{de} rms (fps)								
	Flight Miles	0.75-1	1-1.5	1.5-2	2-2.5	2.5-3	3-3.5	3.5-4	4-4.5	4.5-5
Water	114,300	0.30	0.22	0.08	0.02	0.01	-	-	-	-
Flatland	117,000	0.62	C.43	0.13	0.04	-	-	-	-	-
Low Mnts	45,900	1.16	1.58	0.07	0.03	-	-	-	-	-
High Mnts	36,500	1.34	1.04	0.38	0.10	0.16	0.08	0.02	-	0.01
Total	313,700	0.67	0.59	0.13	0.05	0.02	0.01	0.002	-	0.001

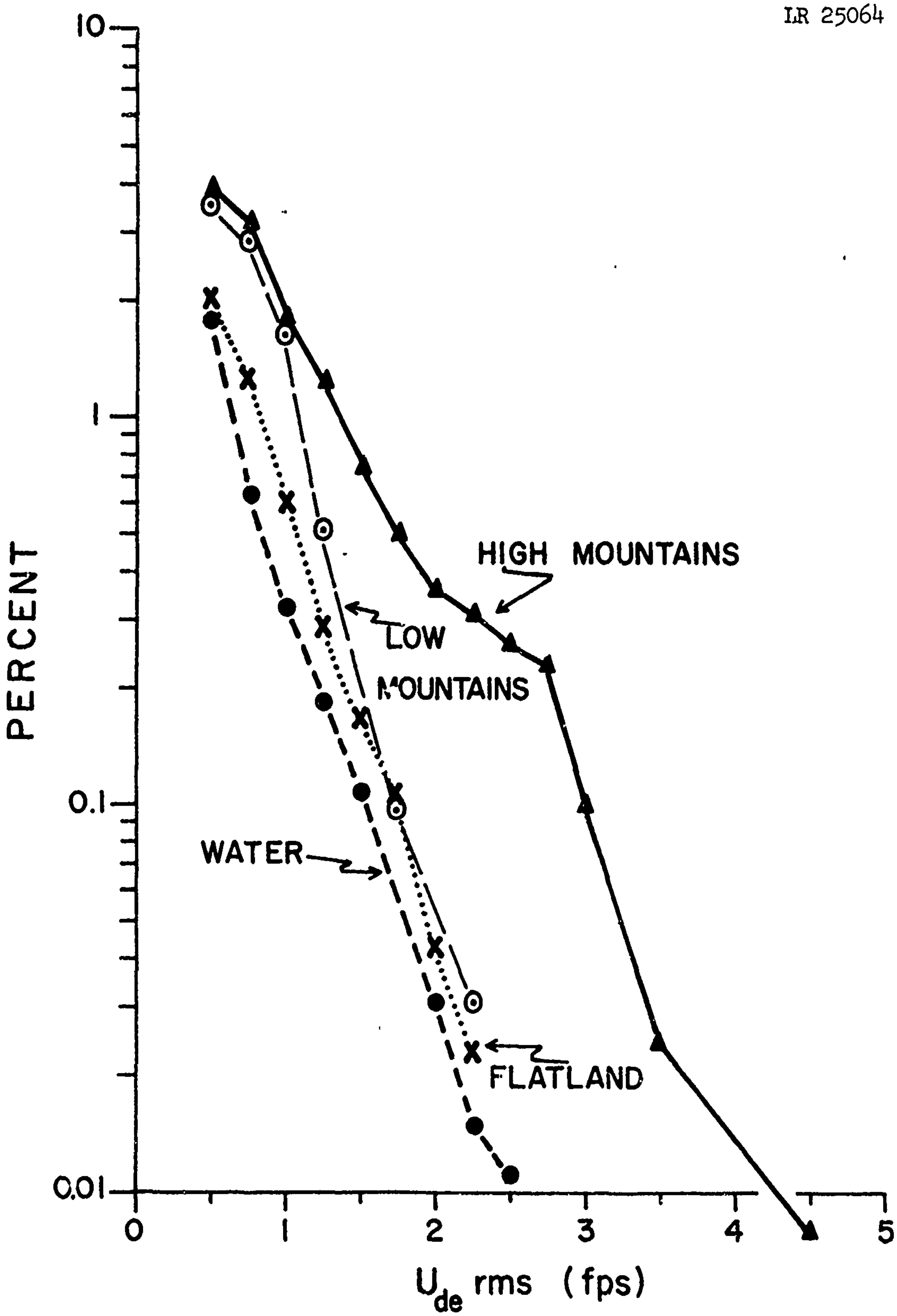

Figure 13. Ratio of flight miles with U_{de} rms equalled or exceeded to total flight miles by terrain. Ordinate scale is logarithmi , expressed in percent.

considerably reduced the bias towards increased percentage of total flight miles in turbulence which results from planned flights into suspected turbulent regions.

After the pattern adjustments were made there remained 7400 miles with U_{de} rms $\geq$ 0.5 fps (2.5 percent of the total flight miles). The cutoff between smooth and turbulent flight used in Ashburn et al (1969, 1970) was closer to U_{de} rms = 0.4 fps. For the Ashburn study 3.1 percent of the flight miles were classified as turbulent.

The ratio of turbulent to total flight miles generally increased with terrain roughness (Figure 13) although the difference between all but high mountains was slight for U_{de} rms > 1.5 fps. Turbulence frequencies for flights over water were significantly lower than for high mountain flights, particularly for large U_{de} rms. For example, over high mountains the ratio of flight miles was double that over water and 20 times greater for U_{de} rms $\geq$ 2.5 fps. On the average, U_{de} rms exceeded 2.75 fps in 1 of every 500 miles flown over high mountains while turbulence of this magnitude was unrecorded in 114,000 flight miles over water.

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SECTION III

TRUE GUST VELOCITY MEASUREMENTS

Time histories of the vertical gust velocity (U_v) for 277 turbulence encounters were used in determining the frequency of varying gust changes over intervals not exceeding 5 seconds. These values (referred to as ΔU_v) are tabulated in Table IV. Limiting the period containing the gust change to 5 seconds was done somewhat arbitrarily. Observations of time histories and power spectral density curves suggest that the wavelengths of frequently occurring gusts are distributed over wide intervals.

Table IV lists the number of occurrences of ΔU_v equalling or exceeding various magnitudes by terrain categories. Occurrences for all terrains are also listed. The logarithm of the exceedance value of ΔU_v follows a normal distribution (Figure 14). The percent of total miles above various terrains were: water, 18 percent; flatland, 26 percent; low mountains, 18 percent; and high mountains, 38 percent. In Table IV the total sample distribution for large ΔU_v reflects the high mountain sample since 84 percent of gusts $\geq$ 20 fps were measured on flights over high mountains (89 percent for $\Delta U_v \geq$ 30 fps). The total number of flight miles from which true gust velocity measurements were obtained represents approximately 40 percent of the flight miles used in the U_{de} analysis. Because of the smaller sample available with true gust measurements no adjustments were made in the data obtained from pattern flights.

The number of ΔU_v occurrences per 1000 flight miles that equalled or exceeded various magnitudes are listed in Table V along with the average number of miles flown for each ΔU_v occurrence. Four terrain classes are again represented. The method used to obtain the figures in Table V is as follows:

TABLE IV

NUMBER OF OCCURRENCES OF ΔU_V EQUALLING OR EXCEEDING VARIOUS MAGNITUDES FOR 277 TURBULENCE ENCOUNTERS

		ΔU_V (fps)							
	Turbulent Miles	≥ 10	≥ 15	≥ 20	≥ 30	≥ 40	≥ 50	≥ 60	≥ 70
Water	1568	205	34	7	1	-	-	-	-
Flatland	2310	439	133	46	6	1	-	-	-
Low Mnts	1620	648	158	50	11	3	-	-	-
High Mnts	3390	2436	993	525	145	34	7	2	1
Total	8888	3728	1317	628	163	38	7	2	1

TABLE V

NUMBER OF OCCURRENCES OF ΔU_V EQUALLING OR EXCEEDING VARIOUS MAGNITUDES PER 1000 FLIGHT MILES BY TERRAIN (NUMBER OF FLIGHT MILES PER OCCURRENCE IN PARENTHESIS)

	ΔU_V (fps)						
	≥ 10	≥ 20	≥ 30	≥ 40	≥ 50	≥ 60	≥ 70
Water	3.9 (260)	0.13 (7700)	0.02 (53,000)	0	0	0	0
Flatland	6.9 (150)	0.72 (1400)	0.09 (11,000)	0.02 (63,000)	0	0	0
Low Mnts	15.1 (66)	1.20 (830)	0.26 (3,800)	0.07 (14,000)	0	0	0
High Mnts	26.5 (38)	5.70 (180)	1.60 (630)	0.37 (2,700)	0.08 (13,000)	0.02 (45,000)	0.01 (91,000)
Total	9.3 (110)	1.60 (630)	0.41 (2,400)	0.10 (11,000)	0.02 (59,000)	0.005 (200,000)	0.003 (400,000)

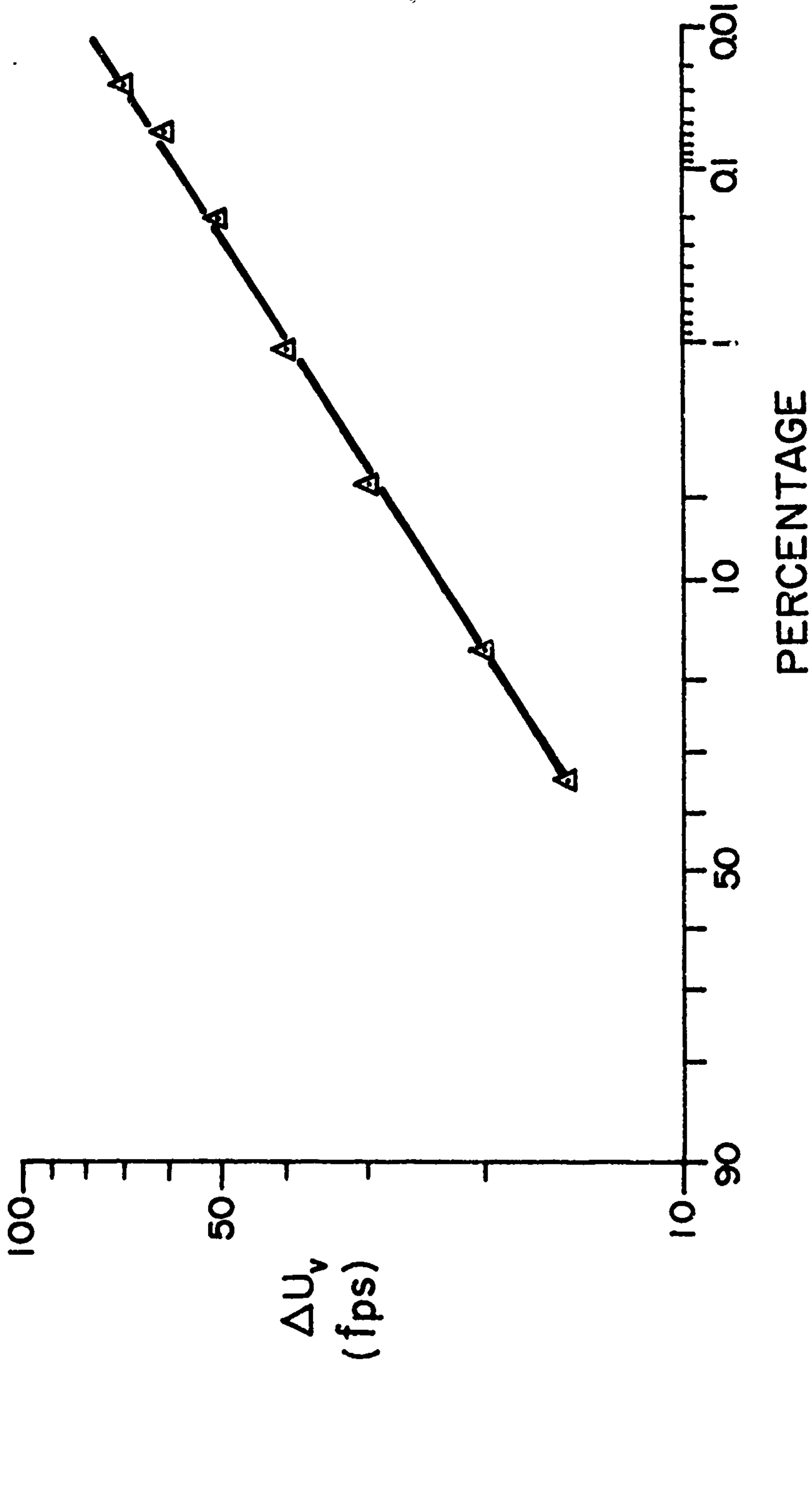

Figure 14. Percentage of ΔU_v occurrences $\geq$ 10 fps per 10 mile turbulent segments plotted as a function of U_{de} $\overline{rms}$ for 277 turbulent encounters.

(1) The average number of occurrences of $\Delta U_v \geq 10$ fps per 10 mile turbulence segments were plotted as a function of U_{de} rms for 277 encounters (Figure 15).

(2) The relationship between ΔU_v and U_{de} rms in (1), obtained from a least square linear regression, was used along with the frequency distribution of U_{de} rms (Table III) in determining the occurrences of $\Delta U_v \geq 10$ fps per 1000 flight miles (Column 1, Table IV). For example, consider a 1000 mile flight segment over water. In 3 miles of this segment (0.3 percent) U_{de} rms would be between 0.75 and 1 fps (0.875 fps average) and, from Figure 15, there would be 3/10 x 2 or 0.6 gusts with $\Delta U_v \geq$ 10 fps. For the U_{de} rms range 1 to 1.5 fps (2.2 miles in a 1000 mile segment) $\Delta U_v \geq 10$ fps would occur 1.5 times, 1.1 times for $1.5 < U_{de}$ rms < 2 fps, and so on There would be a total, then, of 3.9 occurrences of $\Delta U_v \geq 10$ fps for each 1000 mile flight segment.

(3) Occurrences of ΔU_v equalling or exceeding values greater than 10 fps were estimated by taking the product of ΔU_v occurrences ≥ 10 fps (Column 1, Table IV) and the ratio of occurrences ≥ 20 fps, 30 fps, etc., to occurrences of ≥ 10 fps listed in Table III. Considering again the flights over water, there were 7 occurrences of $\Delta U_v \geq 20$ fps, or 3.4 percent of those ≥ 10 fps (Table III). In Table IV the 0.13 occurrences of $\Delta U_v \geq 20$ fps is the product of 0.034 and the 3.9 occurrences ≥ 10 fps.

The average number of flight miles between occurrences of ΔU_v are plotted as a function of the magnitude of ΔU_v equalled or exceeded and terrain in Figure 16. The ordinate scale is logarithmic.

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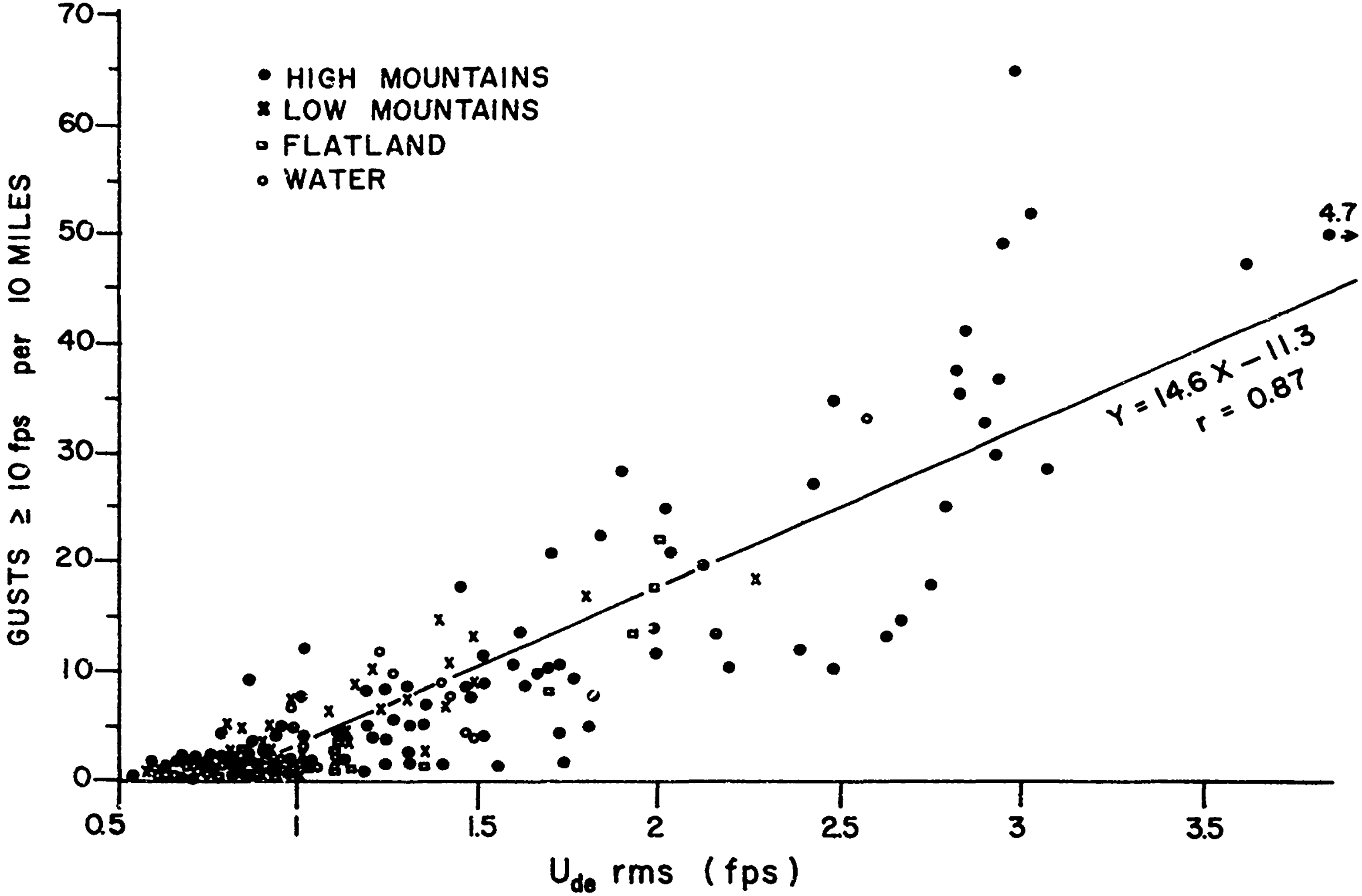

Figure 15. Average number of occurrences of $\Delta U_v \geq 10$ fps per 10 mile turbulent segments plotted as a function of $\overline{U_{de}}$ for 277 turbulent encounters.

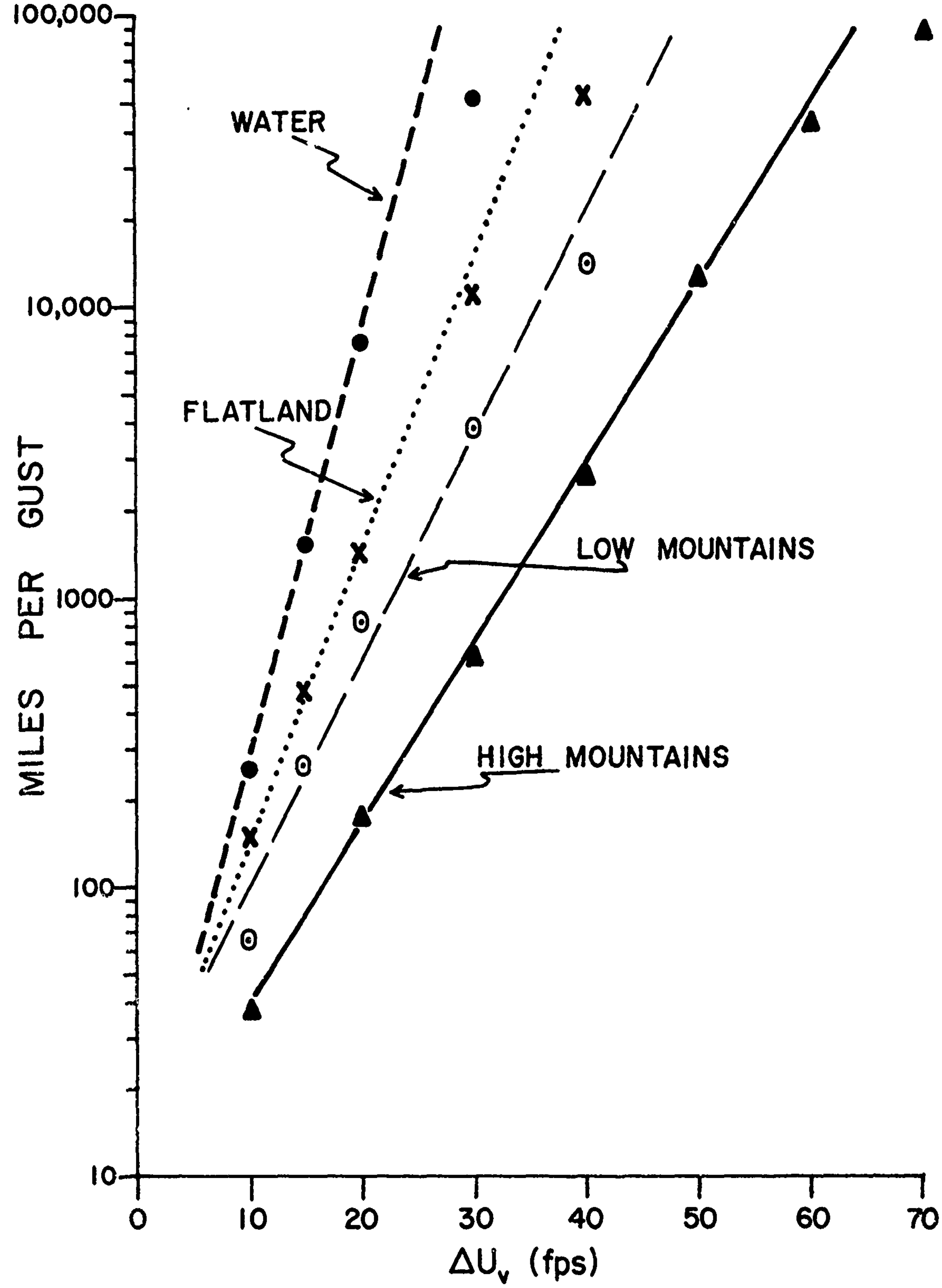

Figure 16. Average number of flight miles between ΔU_v occurrences as a function of ΔU_v magnitude equalled or exceeded and terrain. Ordinate scale is logarithmic.

SECTION IV

TURBULENCE AS A FUNCTION OF ALTITUDE

Curves showing the ratio of flight miles with U_{de} rms equalled or exceeded to total flight miles as a function of altitude and terrain are presented in Figure 17. The ordinate is scaled logarithmically, expressed in percentage of total flight miles. Only two terrain categories are used (water-flatland and mountains), this increasing the sample size in each category. The following observations are noted:

(1) For a given ratio of U_{de} rms miles to total miles the magnitude of U_{de} rms is greater for mountain cases in all altitude bands. To illustrate, in 0.1 percent of flight miles below 55,000 ft, U_{de} rms $\geq$ 1.9 fps for flights over flat terrain and $\geq$ 2.8 fps for flights over mountains. The 0.1 percent figures for 55,000 to 60,000 ft are 1.4 fps (flat) and 2.3 fps (mountains) and, for above 60,000 ft, 0.9 fps (flat) and 1.9 fps (mountains).

(2) The slopes of both sets of curves become steeper with increasing altitude suggesting that the occurrence of large U_{de} rms is less probable as flight altitude is increased.

(3) The steeper slopes of the water-flatland curves denote that turbulence decreases with altitude at a greater rate over flat terrain than over mountains. At altitudes below 55,000 ft U_{de} rms $\geq$ 2 fps occurred 4 times more often for a given number of miles flown over mountains than over flat terrain, 13 times more for the altitudes between 55,000 and 60,000 ft, and 100 times more for flights above 60,000 ft (extrapolation of the water-flatland curve was necessary to obtain the latter result).

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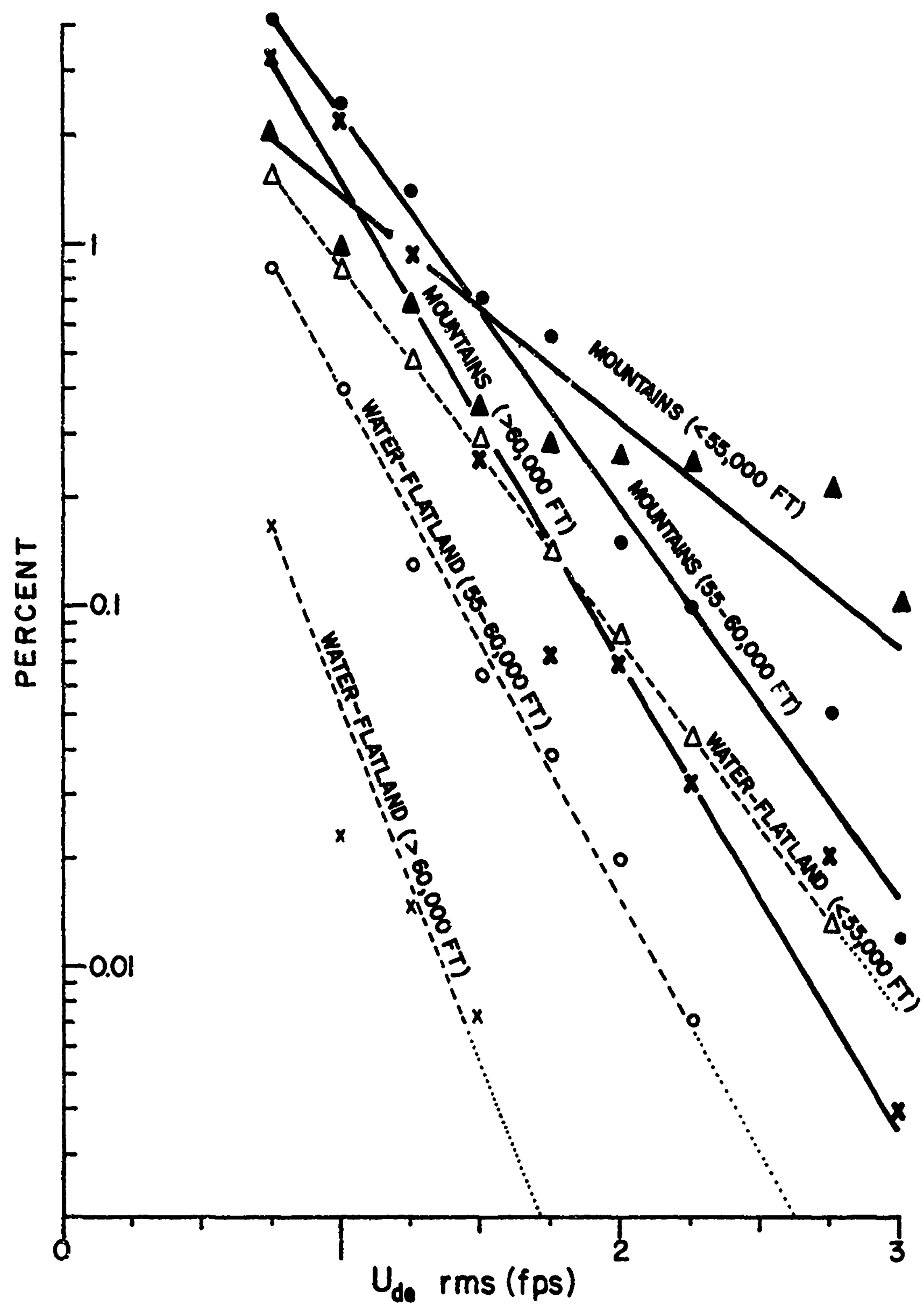

Figure 17. Ratio of flight miles with U_{de} rms equalled or exceeded to total flight miles by altitude and terrain. Ordinate scale is logarithmic.

The variation in turbulent and total flight mile ratios with terrain differences for flights above 60,000 ft is further illustrated by observing (Figure 17) that U_{de} rms $\geq$ 2 fps occurred, on the average, in 1 of 1300 miles flown over mountains and 1 of 130,000 miles over water and flatland. Also, there was no turbulence with U_{de} rms $\geq$ 1 fps in 34,000 flight miles over water while 2.5 percent of the miles over mountains contained turbulence of this magnitude.

SECTION V

ESTIMATING THE PROPORTION OF FLIGHT DISTANCE IN TURBULENCE

The proportion of flight distance in turbulence (P), i.e., the ratio of mil in turbulence to total flight miles, was determined by Crooks et al (1968) using cg normal acceleration data. The figures were later revised by Ashburn et al (1969) to account for bias due to repeated flight patterns, and classification by terrain was added. The values of P depended in part on the subjectivity used in the sampling and analyzing of flight data.

In general, the determination of P should include reference to the following:

(1) The cutoff point between turbulence and smooth flight.

(2) Minimum and maximum lengths of turbulence runs.

(3) Range in frequency of the measurements.

Selection of beginning and end points of turbulence runs can be affected by stipulating a limitation on the total number of runs (which usually results in combining separate encounters) and by difficulties arising due to the sporadic nature of turbulence. These shortcomings result in the inclusion of "smooth" data within the turbulence records, i.e., patches of flight data with intensity below that assigned to the overall run. The result is an array of records with various degrees of non-stationarity.

An example of non-stationarity in vertical gust velocity time histories is illustrated in Figure 18. The top trace shows a fairly stationary run of moderate turbulence with a vertical gust velocity rms (λ_{max} = 2000 ft) of 2.26 fps. The middle trace contains turbulence of variable intensity but

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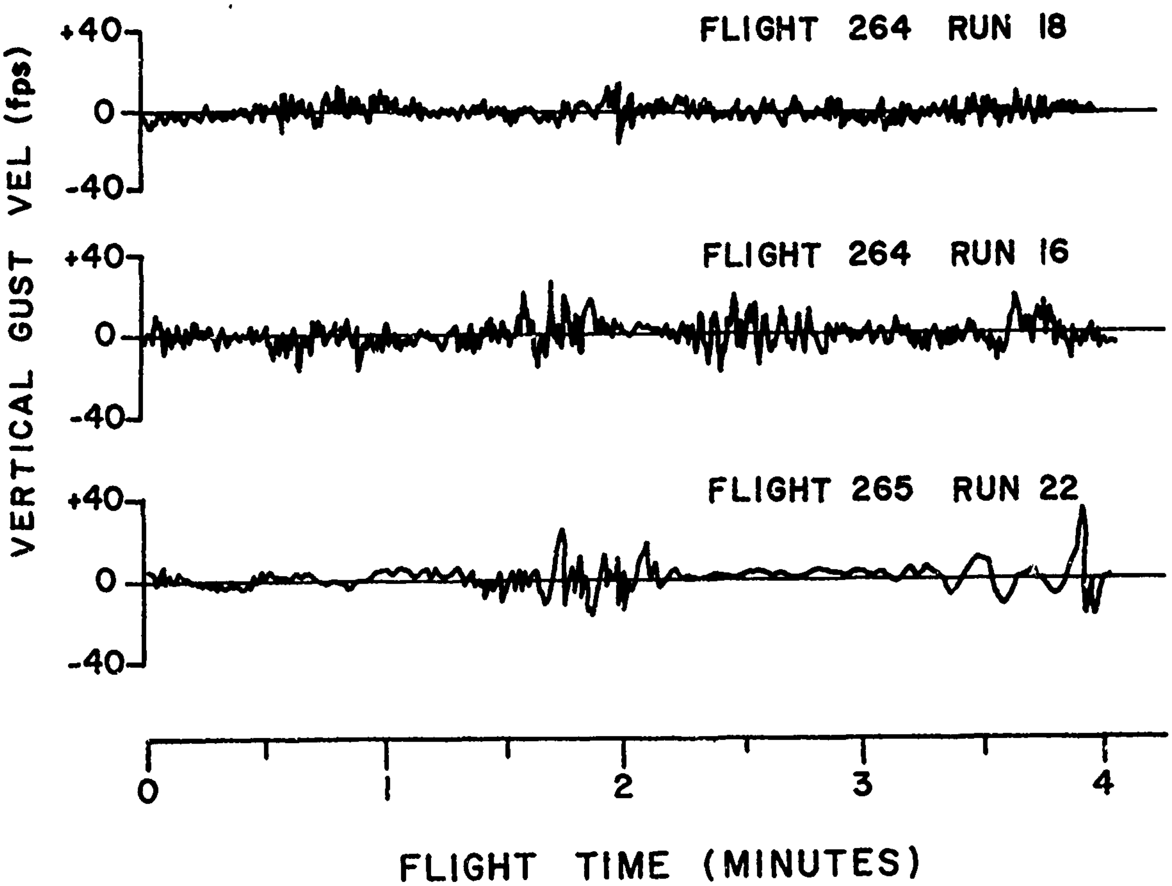

Figure 18. Time histories of vertical gust velocity for three HICAT runs.

was rated severe with an rms (λ_{max} = 2000 ft) of 3.07 fps. Notable in the bottom trace are the patches of "smooth" data. Crooks et al (1968) classified this run as severe despite the rms being only 2.12 fps.

The time in moderate turbulence is reduced substantially when only those portions of the records which contain gust velocity fluctuations exceeding certain values are considered. An effort was made to specify P by analyzing time histories of true gust velocities for 277 HICAT runs (27 percent of the turbulence encounters from which Crooks et al (1968) and Ashburn et al (1969) were able to determine P). Table VI lists (by intensity) the comparison of flight distance in turbulence as determined by editing the time histories (as outlined below) to the total distance included in the 277 runs. That portion of a time history was considered as light turbulence when any of the three gust velocity components had recurring changes of 8 fps but less than 15 fps in periods of around 5 seconds or less. If the changes equalled or exceeded 20 fps the turbulence was classified as moderate (moderate-severe or severe for changes of 35 fps or greater). "Smooth" flight was implied if there were no recurring changes of 8 fps.

The amount of turbulence experienced by the U-2 is shown (Table VI) to be considerably less when "smooth" or low intensity portions of runs are identified. The cg peak method of classifying turbulence (Crooks et al, 1968) tended to represent the intensity of most runs by that of the most intense portion. In the time history evaluation method, time in turbulence $\geq$ light has been reduced 30 percent and moerate or greater turbulence 70 percent.

The ratio of turbulent to total flight miles (P) was computed for all HICAT flights by reducing the figures indicated in Ashburn et al (1969) by the amounts determined in observing the true gust velocity time histories. Comparison of P's derived from cg acceleration measurements (Ashburn et al 1969) and those from time history evaluations are listed by terrain in Table VI. Both sets of values may be thought of as being low because turbulence durations of 10 seconds or less were not included in the original processing

TABLE VI

(A) RATIO OF P'S OBTAINED BY EDITING TRUE GUST VELOCITY TIME HISTORIES TO P'S LISTED IN ASHBURN ET AL (1969)

(B) COMPARISON OF ASHBURN P'S TO EDITED TIME HISTORY P'S

	(A)			(B)			
	Ratio: Time History P / Ashburn P			Ashburn P's (%)		Time History P's (%)	
	≥ L	≥ M	≥ MS	≥ L	≥ M	≥ L	≥ M
Water	0.66	0.27	*	2.7	0.5	1.8	0.1
Flatland	0.66	0.18	0.11	2.7	0.5	1.8	0.1
Low Mnts	0.75	0.30	*	3.6	1.5	2.7	0.5
High Mnts	0.72	0.46	0.32	4.9	1.8	3.5	0.8
All Terrain	0.70	0.33	0.29	3.1	0.8	2.2	0.3

*Less than 1% of turbulent miles in this category

of the data by Crooks et al (1967). However, several factors contribute towards possibly increasing turbulence time above what would be expected from a series of flights based on routine or random rather than search procedures. These are as follows:

(1) Experienced meteorologists directed many HICAT flights towards regions of expected turbulence.

(2) Pilots commonly would search over wide altitude ranges until turbulence was found.

(3) Flights over high mountains were most frequent in winter, a season with maximum storms.

(4) Around four times as many miles were flown over mountains than would be expected if the flights had been randomly distributed throughout the world (Ashburn et al, 1970).

SECTION VI

SUMMARY

On the basis of evaluating records obtained during the HICAT program the following observations have been determined:

(1) There was considerably larger percentage of flight miles over high mountains with turbulence, especially moderate or greater, than over flat terrain.

(2) The average number of flight miles between occurrences of vertical gusts decreased substantially from flights over flat terrain to flights over high mountains, the difference again becoming greater for more severe turbulence.

(3) Turbulence decreased with altitude over all terrain but at a more rapid rate over water and flatland than over mountains.

(4) The ratio of turbulent to total flight miles was largely overestimated in earlier evaluations because "smooth" or less intense flight records were not properly identified.

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